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THESIS

**DESIGN AND CONSTRUCTION OF A ONE
METER ELECTROMAGNETIC RAILGUN**

by

Fred Charles Beach

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Thesis Advisor: Richard Harkins

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A one meter Electromagnetic Railgun was designed and constructed to serve as a test bed for research into alternative armature materials, rail/armature plasma effects, and current pulse forming techniques. A modular approach was used to allow independent changes in power supply, pulse forming network, bore configuration, and gun augmentation.

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DESIGN AND CONSTRUCTION OF A ONE METER ELECTROMAGNETIC RAILGUN

Fred C. Beach

Lieutenant Commander, United States Navy

B. S., University of Oklahoma, 1982

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The acceleration of projectiles through the use of electromagnetic forces (Railguns) has many advantages over conventional methods. Foremost are the higher velocities which can be achieved and the reduction in firing platform sensitivity to hits. Projectile velocities on the order of 3-4 kilometers per second allow the use of "kinetic energy kill" projectiles which are effectively inert munitions. Additionally, by using purely electromotive force for the acceleration, the need for explosive propellents is elliminated.

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I. INTRODUCTION

A. HISTORY

Electro-Magnetic (EM) Accelerators have received varying levels of interest for many years, and dozens of large and small scale prototypes have been constructed around the world. In the United States, the first formal studies of their application in ordnance occurred in 1977. That year, Dr. Harry Fair, then the head of the Propulsion Technology Branch of the Army Research and Development Command in Dovern, N.J., inquired whether any of the EM Accelerators being developed at MIT might have military uses. This led to the formation of an interagency steering committee and advisory panel to coordinate efforts between DOD and other centers of expertise [1].

A wide range of proposals and prototypes sprang up in most of the national and military labs during the heyday of the Strategic Defense Initiative Organization (SDIO) in the mid to late 1980's. These concepts ranged, in scope, from ground based anti-armor weapons to ballistic missile interceptors fired from platforms in earth orbit. With the end of SDIO, the funding for many of these programs ended. At present, the majority of the surviving work on railguns in this country is concentrated at the Center for Electromechanics at the University of Texas at Austin (CEM UT).

An example of the ongoing work at CEM UT is the construction and testing of a skid mounted, compulsator-driven 30-mm rapid-fire railgun system. This compact, lightweight test bed is to be capable of firing three, five-round salvos of 185-gram payloads (95 gram sub projectile mass) to 1.85 km/s at a firing rate of 5 hz. This system is to be the prototype for a weapon which is envisioned for use on the Amphibious Assault Vehicle (AAV) and is being jointly funded by the United States Marine Corp, and the U.S. Army ARDEC Close Combat Armaments Center [2].

B. THE CASE FOR ELECTROMAGNETIC GUNS

1. Velocity Limitations of Conventional Guns

The rationale for increasing the velocity of projectiles is twofold. The first deals with the ability to increase weapons range through higher velocities while at the same time reducing the time of flight of the projectile over a fixed range. Both of these enhance the safety of the user. By extending the lethal range of the weapon the user is removed from or placed near the limit of the enemy weapons' range and by having a higher velocity projectile, he has a higher probability of prevailing in a "quick draw" situation.

The second rationale for higher velocities involves the relationship between velocity and kinetic energy of a projectile, $K.E. = \frac{1}{2}mv^2$, which shows that a doubling of a projectiles mass only doubles its kinetic energy whereas doubling its velocity increases its kinetic energy by a factor of four. This can be exploited by using extremely high velocity projectiles which have the capability of achieving "kinetic energy kills" thereby eliminating or reducing the need for explosive projectiles.

Conventional propellent guns, including electrothermal and chemical guns, accelerate projectiles by generating large pressures behind the projectile inside the barrel. Higher velocities are achieved by either increasing the pressure in the barrel or extending the time over which the pressure is applied. The first method requires building stronger (heavier) barrels with a practical limit being reached as the weight of the gun exceeds that which can be used in a tactical environment. The second method involves extending the length of the barrel, thereby extending the time over which a given pressure is applied. This approach has received a great deal of attention of late with "Super Guns", but once again, except for strategic applications the length of these barrels rapidly exceeds that which can be reasonably fielded.

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2. Sensitivity of Conventional Munitions/Propellants

The survivability of a weapon platform and its crew in battle has always been a concern and in recent history, a major concern. With the introduction in this country of legislation requiring "Live Fire Testing" of all developmental weapon systems and platforms, it has become an almost overriding concern. Paramount in the determination of the survivability of a system or platform is the analysis of how the volatile components will respond to the effects of a weapons hit. The surest and simplest way of reducing these conflagration and or sympathetic detonation problems is to reduce the amount and types of volatile materials involved.

An EM weapon's ability to achieve target kills using completely inert projectiles eliminates the problem of protecting explosive projectiles from sympathetic detonation during a hit or from heat produced by conflagration following a hit. A similar reduction in vulnerability is obtained through the elimination of explosive propellants. EM weapons require only electrical current to operate. This can be generated in numerous ways, none of which require the introduction of any new volatile materials. In effect, fielding an EM weapon or adding one to a weapon platform is equivalent, from a vulnerability perspective, to adding additional inert material.

3. Where is the EM Gun a Good Choice

While projectile velocity is a high priority in most ordnance applications, the benefits of increasing it in some areas may be secondary to such performance characteristics as rate of fire, system weight, simplicity of maintenance, mean time between failure, and environmental operating envelope, to name but a few. The design and operating characteristics of EM guns make them an excellent choice where specifications call for high projectile velocity (armor piercing/kinetic energy kill), low system vulnerability, low firing signature, extended projectile shelf life, selectable lethality ("Dial a Velocity"), ease of projectile storage/handling/resupply, and minimal environmental impact.

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The main battery of the M1A2 Abrams tank is an excellent example of an application for which an EM gun is ideally suited. In their main role as anti-armor weapons, tank guns have grown in length over time in an attempt to achieve ever higher projectile velocities in order to overcome increasingly sophisticated armors. Current 120 mm rounds such as the M829A1 which has a DU (depleted uranium) penetrator were very successful against Soviet built T-72 tanks during the Gulf War. However, to achieve their armor penetrating characteristics, these sub caliber penetrator rounds need to be accelerated to a muzzle velocity approaching 1670 m/s. This is accomplished using propellent charges which are at the very limit of the gun's design, resulting in severe bore erosion and significant reduction in barrel service life. EM guns can accelerate penetrating rod type projectiles to muzzle velocities of 2000 - 3000 m/s with a comparable barrel length.

An equally attractive characteristic of the EM gun is the absence of projectile propellants. Of the approximately 50 rounds carried by the M1A2, 80% are stowed in the turret and constitute the greatest vulnerability concern of the tank. By utilizing EM gun technology this concern is completely removed. The elimination of the propellent charges also frees up nearly 75% of the space previously used for ammunition storage which could then be utilized for the EM guns energy storage machinery and additional projectiles. Another benefit of the higher velocities attained by the EM gun is the ability to obtain superior target damage results with lighter penetrators thereby eliminating the need for DU penetrators and their associated hazards to personnel and the environment.

From a naval perspective, the employment of an EM gun in the role currently filled by the Mk-45 5"/54 would greatly increase the ranges at which Naval Gunfire Support (NGFS) could be conducted. At the same time, the need for powder magazines and their associated sprinkler systems could be eliminated. EM technology could also be employed in either manned or automated small caliber (25-35 mm) weapons mounted on deck for use in defense against small boat or light aircraft

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attack. The extremely high velocity and subsequent flat trajectory of an EM gun would enable it to be used in a nearly "point and shoot' mode for short range engagements.

Another area in which an EM guns unique operating characteristics could be exploited is in OOW (Operations Other Than War). By the nature in which an EM gun accelerates its projectiles through electrical action it is possible to "detune" it to achieve a broad range of selectable velocities below that of its maximum capability. As such, a weapon could be designed with the capability to fire a generic projectile such as a rubber bullet over a wide range of velocities from nonlethal, to armor piercing, by simply adjusting a dial on the weapon. This type of flexibility from a single weapon and projectile combination could generate a true paradigm shift in the way we envision not only the design and use of firearms but their definition as well.

II. EM GUN THEORY

A. BASIC OPERATION

The force generated in a Railgun is the result of the Lorentz Force created by the flow of electrical current through the armature interacting with the magnetic field generated by the current flowing through the parallel rails of the gun:

$$\vec{F} = \vec{il} \times \vec{B}, \qquad (2.1)$$

where i is the current flowing through the armature, $\vec{l}$ is the distance between the rails, and $\vec{B}$ is the magnetic field generated between the rails as shown in Figure 1.
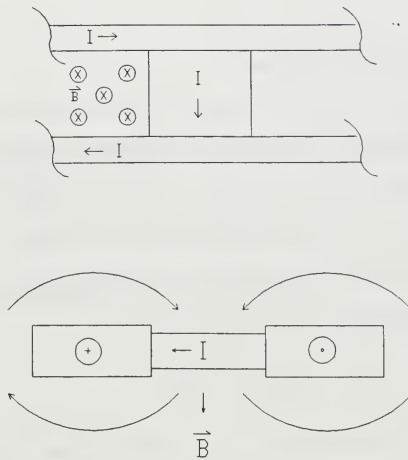

Figure 1. Magnetic field generated by current flow in an EM gun.

A simple circuit diagram for a Rail Gun and its associated power supply is shown in Figure 2.
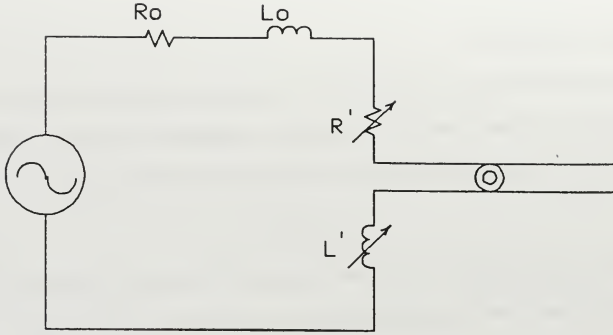
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Figure 2. A simple Rail Gun circuit.

In this initial analysis, the power supply is treated as essentially a black box with a fixed output impedance of: $Z_o = R_o + j\omega L_o$. The rail gun itself is characterized by a linear resistance gradient, R', and a constant inductance gradient, L'.

By treating the gun as a component in this electrical circuit, the Lorentz force generated behind the armature has been shown to be:

$$F_{RG} = \frac{1}{2} * \frac{dL}{dx} * i^2, \qquad (2.2)$$

where i is the current in the rails [3]. For a specific Railgun the inductance can be measured and equation (2.2) becomes:

$$F_{RG} = \frac{1}{2} * L' * i^2, \qquad (2.3)$$

where L' is the inductance per meter of rail pair.

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With equation (2.3) we can now calculate the acceleration for a given Railgun / projectile combination:

$$a = \frac{L'i^2}{2m} \,,$$

(2.4)

where i is the instantaneous current in the gun. Now if we know the current pulse shape, the velocity of the projectile can be determined by integration:

$$v = u + \frac{L'}{2m}\int_0^t i^2 dt,$$

(2.5)

where u is the injection velocity of the projectile into the gun or the initial velocity of the projectile prior to initiating the current pulse. By assuming that the initial projectile displacement is zero, the total displacement is:

$$x = \int_0^t v dt = ut + \frac{L'}{2m}\int_0^t dt'' \int_0^{t''} dt' \left[i(t')\right]^2.$$

(2.6)

Previous work [3] has shown that an EM gun's behavior can be analyzed by defining the electrical action G as:

$$G = \int_0^t i^2 dt,$$

(2.7)

and a parameter H, which is the time integral of G:

$$H = \int_0^t G \, dt.$$

(2.8)

Now equation (2.5) can be written as:

$$v = u + \frac{L'G}{2m}$$

(2.9)

and equation (2.6) can be written as:

$$x = ut + \frac{L'H}{2m}.$$

(2.10)

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G is a parameter which defines the energy dissipated per unit electrical resistance in units of MJ/Ω. From this, it can be shown that there is a direct connection between the acceleration of the railgun projectile and the energy which is resistively dissipated in the circuit during the current pulse. As an example, the resistive energy loss in R_o, defined as W_r, is given by

$$W_r = R_o \int_0^t i^2 dt = R_o G = \frac{2 R_o m (v - u)}{L'}. \tag{2.11}$$

This example demonstrates two things. First, it can be seen that the energy loss is not proportional to the kinetic energy of the projectile as might be expected, but rather, to the projectile momentum. Secondly, the energy demand can be seen as being inversely proportional to the inductance gradient, L' of the gun. This second fact highlights the importance of trying to maximize the inductance gradient while designing the railgun barrel.

B. CURRENT PULSE SHAPE REQUIREMENTS

To obtain exact solutions for equations (2.9) and (2.10), the shape of the current pulse seen by the gun must be specified. In ref. [3], Putley analyses the simple trapezoidal current waveform of Figure 3.

In this simple model of a current waveform, the current rises linearly from zero over a time τ to a constant value of I, where it is held for a time T. The current then falls back to zero once again in a time τ. His previous work [4] showed that with a linear current waveform, where the current varies from i_o to i_f over a time t, that G and H are given by

$$G = \frac{1}{3} t \left[(i_o + i_f)^2 - i_o i_f \right] \tag{2.12}$$

and

$$H = t^2 \left[\frac{1}{4} i_o^2 + \frac{1}{6} i_o i_f + \frac{1}{12} i_f^2 \right]. \tag{2.13}$$
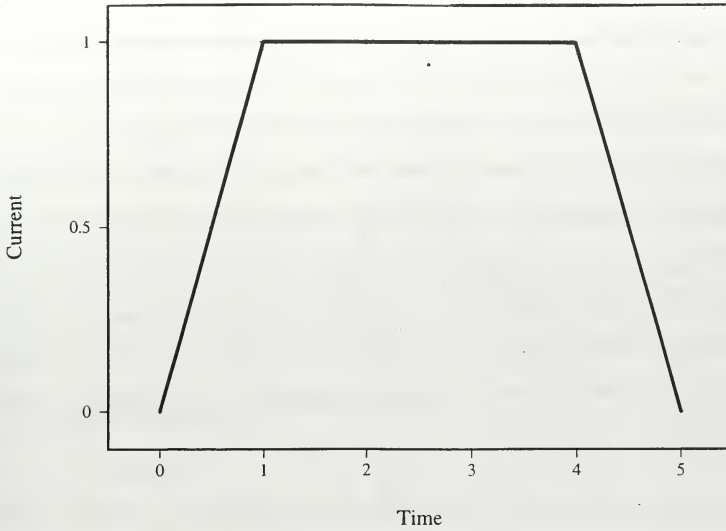
Figure 3. Idealized current waveform.

Using these equations the resistive loss in the railgun's barrel was shown to be:

$$W_b = R't^2 \left[u\left[\frac{1}{4}i_f^2 + \frac{1}{6}i_o i_f + \frac{1}{12}i_o^2 \right] + \frac{L't}{168m} \left[(i_o + i_f)^4 - i_o i_f (i_o^2 + i_f^2) \right] \right]. \quad (2.14)$$

If we now apply these results to the trapezoidal waveform of Figure 3, it is possible to calculate the performance which would be obtained. For instance if we define the projectile travel as X and the muzzle velocity as v_m, then

$$X = u(2\tau + T) + \frac{L'I^2}{12m} (4\tau^2 + 8\tau T + 3T^2) \quad (2.15)$$

and

$$v_m = u + \frac{L'I^2}{m} \left[\frac{\tau}{3} + \frac{T}{2} \right], \quad (2.16)$$

where I is the peak current generated during the pulse. These two equations now

define the performance of a given railgun assuming a simple, symmetric, trapezoidal current pulse. This approximation is very useful for exploring design options for railguns, given a specification for projectile mass and muzzle velocity.

By the nature of the extremely high velocities achieved with EM guns in relatively short barrels, the acceleration and jerk, $J = \dfrac{da}{dt}$, experienced by the projectile can be extreme. This needs to be taken into consideration when designing the type of projectile to be used. If however, the projectile type and construction is a given specification, the current pulse can be modified to accommodate it. Equation (2.4) can be used to calculate the peak projectile acceleration, $\hat{a}$, and then the mean acceleration, $\bar{a}$ is,

$$\bar{a} = \frac{v_m^2}{2X}.$$

(2.17)

Now the peak to mean acceleration ratio, α, is simply

$$\alpha = \frac{\hat{a}}{\bar{a}}.$$

(2.18)

In a similar manner we can obtain a value for the instantaneous value of the jerk experienced by the projectile. Again, from equation (2.4),

$$J = \frac{L'i}{m}\frac{di}{dt},$$

(2.19)

and now the maximum value of jerk, $\hat{J}$, experienced during a trapezoidal pulse is given by

$$\hat{J} = \frac{L'\hat{i}^2}{m\tau}.$$

(2.20)

For the simple trapezoidal pulse shape analyzed here, the rate of change of current is constant during the rise time. Since the jerk is proportional to the current, this gives a slightly higher value of the jerk than might be obtained from a more realistic pulse shape. For example, a sinusoidal current pulse with the same values of peak current

and current rise time would give a value of peak jerk of about 70 % of the trapezoidal pulse's.

With this set of equations, it is now possible to get a rough estimate of the performance obtainable with a given set of specifications. This enables us to do trade off studies such as barrel length required versus muzzle velocity and projectile mass. They also give us insight into the types of power supplies which might be used since they will have a major role in determining the shape and duration of the current pulse that can be generated and consequently in the performance of the gun.

C. POWER SUPPLIES

1. Capacitors

In spite of their relatively low energy density in comparison to compulsators and homopolar generators, capacitors are the power supply of choice in the laboratory environment. Their relatively low cost, simplicity, and reliability also make them competitive in military applications where size and weight considerations are not critical. Aside from their weight, the principle drawback with capacitor power supplies is the requirement for pulse forming networks (PFN's) and transformers. The PFN supplies high current and pulse shaping, and the transformer lowers the voltage and provides a matched load to maximize power transfer.

As an example, consider an EM gun designed to be driven by a 2 kV, 1 MA pulse of 500 µsec duration. To generate this pulse we could use ten, 10 kV, 50 kJ capacitors, parallel connected in pairs to form five modules, each with a capacitance of 2 mF. These five stages can then be connected to form a type E PFN [5], as shown in Figure 4, with a characteristic impedance, Z_o, given by

$$Z_o = \frac{V_{charge}}{2I_{out}} = \sqrt{\frac{L_{total}}{C_{total}}} \ . \tag{2.21}$$

Here, V_{charge} is the total potential on the capacitor bank, I_{out} is the current obtained

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during the discharge, L_{total} is the total inductance of the inductors used between the capacitors, and C_{total} is the total capacitance of the bank. Using Z_o, the duration of the current pulse, t_{pulse}, is given by

$$t_{pulse} = 2C_{total}Z_0 . \qquad (2.22)$$

With the fixed charge voltage of 10 kV and 500 μs current output of 200 kA, equations (2.21) and (2.22) give an impedance of 0.025 Ω and a total inductance of 6.25 μH. As shown in figure 4, the total inductance is obtained by placing a 1.56 μH inductor between each of the five capacitor modules. This 10 kV, 200 kA, 500 μs pulse which has been generated can now be stepped up to the 2 kV, 1 MA, 500 μs pulse required in this example by using a 5:1 current pulse transformer [6].
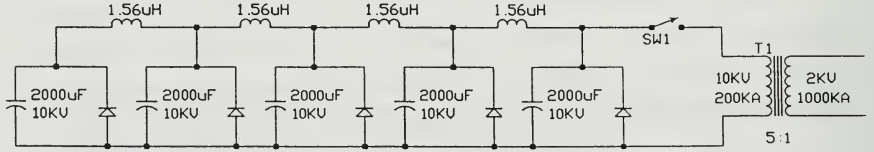

Figure 4. Circuit diagram of power supply.

If the PFN had been used directly to supply the total 1 MA, the characteristic impedance would have changed and the pulse length with it. The power transfer from the PFN to the gun load is maximized due to the impedance matching of the low impedance load to the primary and the current is increased without shortening the pulse length. This combination of impedance matching the load (EM gun) to the power supply using a PFN and stepping up the current to the load using a transformer,

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optimizes the characteristic operating parameters of high energy density capacitors without compromising the current pulse requirements of the EM gun.

2.   Compulsators

Compulsators (Compensated Pulsed Alternators) are low impedance alternators which use flux compression to shape their discharge pulse and thereby increase their peak power. These devices boast stored energy densities on the order of 19 kJ/kg as opposed to 3 kJ/kg for capacitors and 4 kJ/kg for homopolar generators [7]. Compulsators were invented by CEM-UT engineers in 1978 [8] where they have undergone considerable improvement and testing over the last 18 years. The key to the compulsators ability to achieve such high energy densities lies within the large kinetic energies stored in the spinning armature. Driven typically by small gas turbine engines, current designs operate at upwards of 12,000 rpm with rotor tip speeds in excess of 500 m/s.

Recent design improvements include the use of graphite fiber reinforced epoxy composites for the manufacture of the armature rotors. These materials have enabled engineers to manufacture rotors with demonstrated tip speeds as high as 1,200 m/s [9]. Since the energy density of the rotors scales with the square of the tip speed, advances such as this promise even greater improvements in the energy storage for a given mass and consequently even further reduction in the overall weight and size of compulsators.

The most recent product of CEM-UTs' efforts is a 40 MJ, four pole, air core, compulsator which is self excited and regenerates its field energy between each shot. This compulsator was designed and built as a prototype to power the 30 mm rapid fire gun mentioned in the introduction. This machine is an excellent example of how the design of a compulsator can be tailored to match the load requirements of a specific gun. Probability of hit analysis and overall system optimization studies determined that the gun should be capable of firing 15 shots in three, five shot salvos. The shot rate

requirement was 300 rpm with a 2.5 second dwell between salvos. Based on system integration and space constraint issues it was decided that the machine should store enough energy to complete all 15 shots without having to reengage the prime mover and spin back up.

The compulsator is linked to the prime mover via a slip clutch. During the first 100 ms of a shot, a capacitor is discharged into the field coil to provide the seed current for the self excitation. At the end of this time when full field is achieved, the gun fires with a discharge time of 2 ms. Over the next 90 ms, the excitation process is reversed and the energy stored in the magnetic circuit of the gun is recovered as useable kinetic energy in the rotor. During the main discharge when the torque exceeds 400 ft-lb the clutch slips thereby isolating the prime mover from the high decelerating torque. When the discharge is complete the motor resynchronizes with the rotor in 15 ms. Using this method, a small amount of energy is being added to the rotor between shots in a salvo and between salvos. The 15 current pulses generated during a full engagement are shown in Figure 5.
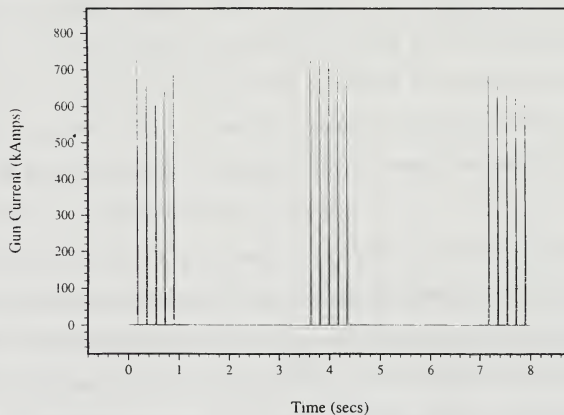

Figure 5. Gun and Compulsator current during an engagement [2].

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During the engagement, the peak current seen by the gun varies from 790 kA for the first shot to 650 kA for the last shot. Approximately 50% of the compulsators energy is used during the fifteen shot engagement resulting in the rotor slowing to about 70% of its original speed. Using a selective passive design [10] for the compulsator resulted in the current pulse shape shown in Figure 6.
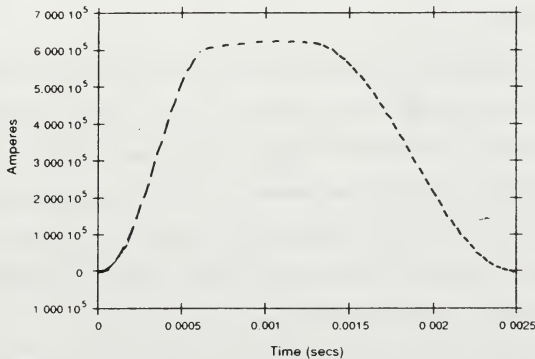

Figure 6. Current pulse generated using selective passive design [2].

This shape results in a peak to mean acceleration ratio of about 2, which keeps the peak jerk experienced by the projectile package to a minimum.

The total weight of the 30 mm gun system is 2200 kg. The compulsator is about 70% of that amount and occupies approximately 1 m^3 of space. By achieving extremely high energy densities and tailoring the design of the compulsator to match the load requirements of the gun, the total system package was kept within weight and volume constraints specified for the Amphibious Assault Vehicle. This was one of the first practical demonstrations of the ability to field an EM gun on a tactical platform.

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D. ARMATURE CONFIGURATION

1. SOLID ARMATURES

Whether they are of the solid or plasma type, the armature is probably the single most critical component in the EM gun. It must conduct currents on the order of 0.5 to 5 MA and be able to withstand accelerations of up to $1 \times 10^7 m/s^2$. Solid armatures predominate in the research work done for weapons applications. Aluminum and copper are the materials of choice due to their high electrical conductivity, ease of machining and low cost.

In weapons applications, the armature usually serves as a means of accelerating a penetrating rod sub-projectile, and, as such, is not a critical component of the projectile package once it has left the barrel. This allows designers to treat the armature as a sacrificial component and permits the use of materials that may erode, ablate, or even completely vaporize as they conduct current during the shot. Attempts to reduce the erosion of the rails of the barrel (usually copper or molybdenum), have lead to aluminum alloys as the preferred material for solid armatures.

Maintaining physical contact between the solid armature and the rails of the gun in order to prevent sporadic electrical arcing is critical. To achieve this, armatures usually have a "bobtail" or "u-shape" geometry as shown in Figure 7. The flow of current through this shape generates a magnetic force which tends to force the trailing arms of the armature against the rails. Even with this type of design, most solid armatures break physical contact with the rails and form an electrical arc at approximately 1,500 - 2,000 m/s [11]. This may occur on one or both armature surfaces and results in a substantial increase in the voltage drop across the gun. This leads to reduced gun efficiency and greater electrical damage to the rails. Solid armatures that operate in this regime are often referred to as transition or hybrid armatures.
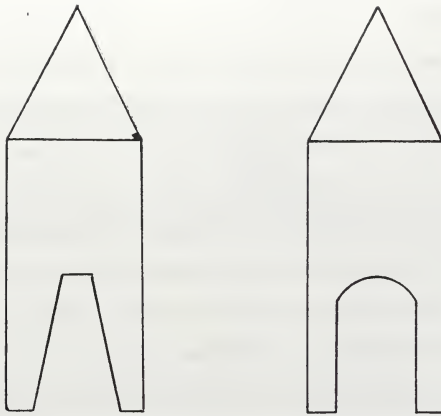
Figure 7. Solid armature geometry.

As more work has been done with solid armatures in this transition area, the term transition armature, has been changed to denote a solid armature design which is experiencing arcing. On the other hand, hybrid armature now denotes a completely separate type of armature design that attempts to promote the formation of an ionized gas (plasma) between the armature surfaces and the rails at higher velocities. This design helps to eliminate the uncontrolled arcing of the transitioning solid armature and reduce rail pitting while increasing gun efficiency.

2. Plasma Armatures

For EM guns operating above 4 km/s the armatures are almost exclusively of the plasma type. Plasma armatures are generated by placing a thin foil or small gauge wire of copper or aluminum between the rails at the breech of the gun behind the projectile. The initial surge of current vaporizes the material, which forms a conducting

plasma cloud. Magnetic forces act on this cloud and compress it against the base of the projectile package.

The voltage drop experienced across a plasma armature is considerably higher than that for a solid design, typically 200 to 600 volts. This results in a large electrical power dissipation loss and consequently damage to the rails and insulators from the high temperatures (25,000 K) produced [11]. Attempts to minimize this effect include initiating the plasma well behind the projectile [12]. This method allows the extremely low mass plasma to rapidly accelerate before colliding with the projectile placed further down the bore. This produces a slower current rise through the plasma armature which results in less rail erosion near the breech of the gun.

The approach described above, and several others have been successful in reducing the rail erosion experienced with plasma armatures in small laboratory EM guns. None of them however, have been successfully scaled up to tactical weapons type applications. Considerable work remains to be done before plasma armatures can be used to boost projectile velocities beyond 4 km/s in tactical EM guns.

E. GUN AUGMENTATION

It is clear from equation (2.3) that the force generated in a rail gun can be increased by either raising the current through it or by improving upon the inductance of the gun barrel. Most early work concentrated on gains in current flow since the gain scales as the square of the current. As the current carrying capacity of armatures appears to have reached a peak, more attention is now focused on gains from increasing the inductance of the barrel.

Augmentation generally refers to the addition of rails running parallel to the primary rails. These rails carry current whose purpose is to increase the magnetic field cutting through the bore. Figure 8 shows how a transaugmented rail gun operates when the current in the augmenting rails is provided from a source separate from that of the primary rails. In this case, the force exerted on the armature is still the
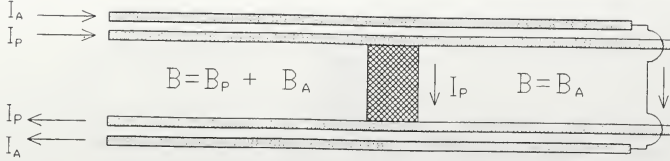
Figure 8. Magnetic forces in a transaugmented railgun.

current in the armature multiplied by the average magnetic field at the armature. However, the magnetic field is now one half the sum of the fields in front of and behind the armature. This is because, unlike the magnetic field from the primary rails which exists only behind the armature B_P, the field from the augmenting rails B_A exists the entire length of the bore regardless of the armature position.

If we express the force in terms of the inductance gradient of the rails as in equation (2.3) with the mutual inductance gradient of the augmenting rails defined as M', the force on the armature is now given by:

$$F_{RG} = \frac{1}{2} * L' I_P^2 + M' I_P I_A. \tag{2.23}$$

This shows that the force in an augmented railgun is the sum of the standard Lorentz force and an additional force which is linearly proportional to the current in the augmenting rails.

The simplest method of augmentation, shown in Figure 9, is to place the augmenting rails in series with the primary rails such that the current in the primary rails is the same as that in the augmenting rails $I_p = I_A$. This type of augmentation
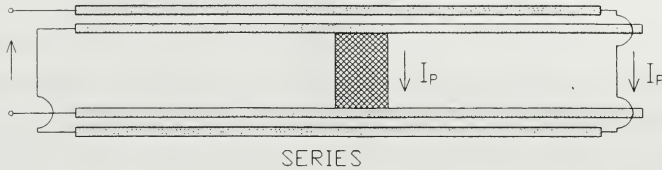
21

Figure 9. Series augmented railgun.

has been used in several laboratory and prototype railguns including the 30 mm gun mentioned in the introduction. The series augmentation requires an approximately 60% lower current and thus higher voltage to achieve the same performance as a gun with no augmentation [11]. As such, one advantage of this type of augmentation is to provide better matching to high impedance power supplies.

A completely different type of augmentation involves the use of permanent magnets to augment the magnetic field in the bore as shown in Figure 10. Much like the effect of augmenting rails, the permanent magnets create a field for the entire length of the bore for which they are installed. Once again, starting with equation (2.3), the force on the armature is now:

$$F_{RG} = \frac{1}{2} * L'I^2 + B*I*D, \tag{2.24}$$

where B is the magnetic field generated by the magnets and D is the distance between the rails. By using rare earth magnets, fields on the order of 1 to 2 Tesla can be achieved without great difficulty. This type of augmentation provides substantial acceleration forces when the current in the rails is still too small to generate significant
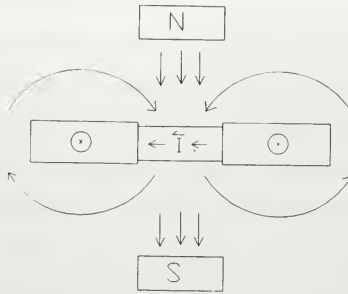
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Figure 10. Permanent magnet augmented railgun.

magnetic fields. The result is a gain in efficiency by taking advantage of the lower currents present during the current pulse rise and decay periods as well as adding to the magnetic field generated by the current in the rails during the rest of the pulse.

III. TEST BED EM GUN

A. GUN DESIGN AND FABRICATION

The one meter electromagnetic (EM) railgun was designed and constructed to serve as a test bed for research work in the field of EM acceleration as well as for work in plasma effects, pulsed power, and hypervelocity impact. The largest constraint imposed on the design and fabrication of the gun and its associated power supply was cost. The entire budget was 1,200 dollars. This required the use of preexisting and borrowed parts and materials wherever possible. The small budget constrained the size and initial operational capability of the gun. It also forced the use of previously untried methods and materials which are explained in the following discussion.

The test bed EM gun design had a 1/4" x 3/4" rectangular bore. This decision was based upon a small scale gun that had been built previously. This small gun had a 1/8" x 3/4" bore and was augmented by a row of rare earth (Neodymium Iron Boron) magnets placed above and below the bore. It fired 3/64" thick, 3/4" diameter graphite discs weighing 0.5 g and was powered by a small bank of 330 volt photoflash capacitors. The large gun was envisioned as a scaled up version of the smaller model, initially using the same augmentation method and projectile material. The length of the gun was determined from several calculations using equation (2.24). For the expected projectile masses of 1-5 g, one meter would be adequate to accelerate to velocities up to 3000 m/s, given a large enough power supply. Just as important was the fact that the longest 1/4" thick, copper bar stock to be found in the Physics Departments store room was 40". For ease of fabrication and because it was available, the body of the gun was manufactured out of Phenolic.

The basic design was a clamshell consisting of two blocks of phenolic each 40" long, 1.375" thick and 3.5" wide. Each block had a 2.25" wide channel cut 3/16" deep running the length of the block to accept the copper rails and a pair of 1/16" phenolic

sheets. As shown in Figure 11, the two phenolic blocks where secured with bolts
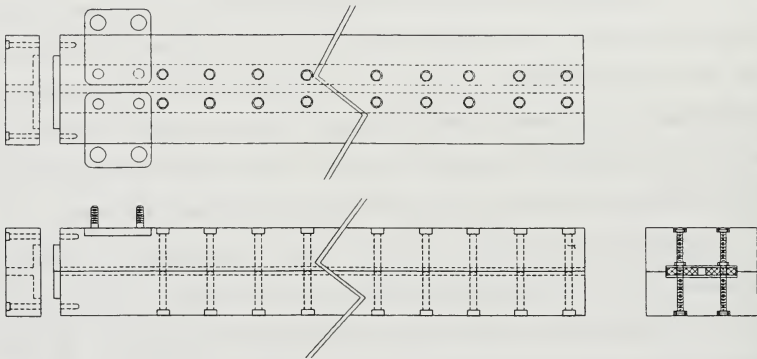which ran through the rails and had a breech block secured to one end.

Figure 11. One meter railgun design.

The permanent magnets where 3/4" wide by 1/2" thick and were to run the length of
the barrel both above and below the bore. Unfortunately, the cost of the 64 magnets
required for the augmentation was approximately 450 dollars and as such were not
procured for the initial operation of the gun. Space was also left to the outside of each
rail to allow for the addition of augmenting rails in the future.

A 1/4", low pressure, air fitting was attached at the breech block to allow for initial acceleration of the projectile by means of a compressed gas charge. Plexiglass windows were placed above and below the bore at a point 4" from the breech. An IR source was used as a means to trigger the current pulse from the power supply as the projectile passed. This method was used to ensure that the projectile was far enough from the breech to eliminate any influence from anomalies in the magnetic field near the end of the rails. It also guaranteed that the projectile would be moving when the current pulse was initiated so that the power supply would not have to overcome the rest inertia of the projectile.

Electrical connection to the rails was made through four, 1/2" threaded copper studs which passed through holes in the upper phenolic block. One pair of these studs threaded into the breech end of each rail. Plates of 1/4" copper were bolted to each pair of studs where they protruded from the top of the gun and served as connection points for the power cables. Cabling between the gun and each terminal of the power supply consisted of a pair of 2/0 welding cables sheathed with high pressure plastic tubing for additional high voltage protection.

B. POWER SUPPLY

The foundation of the power supply was four, 100 μF, 10 kV, high energy capacitors which were left over from a previous, unrelated, experiment. Their 20 kJ of energy at full charge was far short of the 100 - 150 kJ which could be used by the one meter gun. However, as they were "free", the power supply was built around them, but with adequate excess capability should larger capacitors become available in the future. The capacitors were configured in parallel with thick copper bus bars and mounted in a moveable wooden cart. The top of the cart was used for the layout of both the capacitor charging circuitry and the trigger pulse generator and trigger switch components.

The electrical schematic for the power supply and the current pulse transformer is shown in Figure 12.
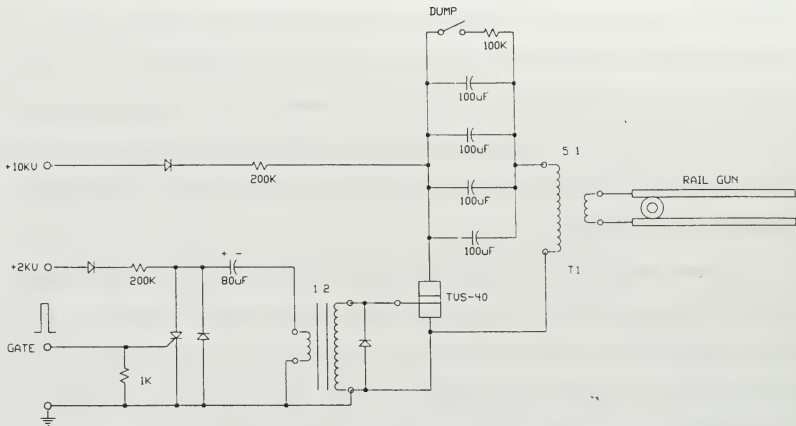

Figure 12. Power supply schematic.

The most unique component of the power supply is the TVS-40 vacuum switch. This device, of Soviet design and construction, was obtained through Maxwell Labs. It has the ability to transfer 100 Coulombs of charge in a single firing at up to 20 kV and 100 kA [13]. This type of switch was chosen over ignitrons and SCRs because of its simplicity, durability, small size, and most importantly, low cost.

The majority of the components in the power supply are dedicated to generating the 2 kV, 1 kA, pulse used to trigger the TVS-40. This was done with an 80 μF, 2 kV capacitor which was discharged via a high current SCR into a homemade transformer which then provided a pulse to trigger the switch. The switch optimally requires a 5 kV, 1 kA, 2 μs pulse. However, for the modest discharge passed through the switch by the 20 kJ capacitor bank, the smaller, faster pulse generated here was more than

adequate.

C. CURRENT TRANSFORMER

The estimated discharge time for the power supply firing into the gun load was 100 µs. With this discharge time, even at full charge, the capacitor banks' 4 coulombs of charge would only generate an average discharge current pulse of 40 kA. Without the permanent magnet augmentation, this current would have been inadequate to generate any significant force on the armature. It was determined that the best solution would be to manufacture a step up current transformer, assuming that it could be done for less than about 100 dollars.

The transformer was modeled after a prototype designed and manufactured by Pappas, Driga, and Weldon in a collaboration between the U. S. Army Armament Research and Development Center and CEM-UT. Presented in [6], their design was a coaxial, air core, pulse transformer envisioned for use in matching high impedance capacitor bank power supplies to low impedance railgun loads. The design seemed an ideal solution to our low current dilemma and a scaled down version was constructed.

The secondary was fabricated from 3/4" ID soft copper tubing. This tubing was bent into a five turn coil around an 19" diameter form. The coil was then cut axially on one side to form five individual helical loops. The loops were electrically parallel connected to two large copper bus bars by soft soldering them into threaded female plumbing fittings which had been screwed into threaded holes in the bus bars. The two bus bars were then clamped together with phenolic blocks after a phenolic insulating plate with holes matching those in the bus bars had been placed between them. This then constituted a single turn primary made up of five loops arranged to form a five turn helical path for the primary.

The primary was made from a 30 foot section of large gauge coaxial cable. The outer layer of insulation and the braided copper sheath were stripped away leaving

only the 3/16" diameter inner conductor and its thick plastic insulation. The outer diameter of this remaining cable was just small enough to fit through the 3/4" ID copper tubing of the secondary. With a bit of effort, this 30 feet of primary was threaded through the secondary, completing the transformer, as shown in Figure 13.
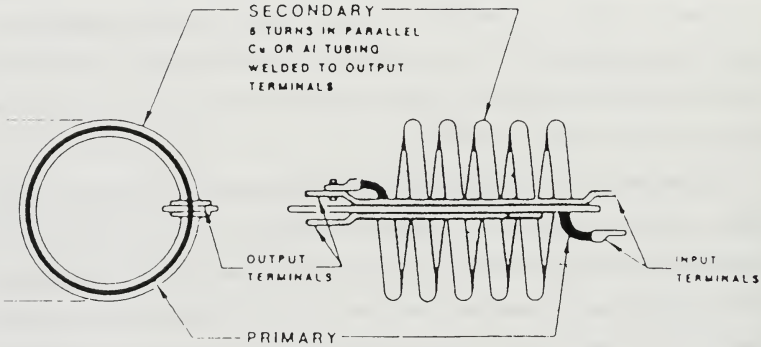

Figure 13. Coaxial, air core, current transformer [6].

The coupling efficiency k, of this type of design was determined by Sadedin in ref [14], to be given by:

$$k = 1 - \frac{\left[\ln \frac{r_o}{r_i} + \frac{1}{4}\right]}{k \pi N \frac{R}{l}}, \tag{3.1}$$

where r_o and r_i are the radii of the outer and inner conductors, R and l are the radius and length of the transformer, and N is the number of turns. For the 19" diameter, five turn transformer, equation (3.1) predicted a coupling efficiency of 91%. With the

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estimated 40 kA, 10 kV input of the power supply, the transformer would then provide a nominal 200 kA, 2 kV, 100 μs pulse to the gun.

Three aluminum braces were added to the transformer axially at 90° intervals to stiffen the structure against the magnetic forces it would experience. Twisted pairs of solid 3/0 cable were used to connect the secondary input and output to the gun and the 2/0 welding cable pairs from the power supply were attached to the ends of the primary. The unit was then mounted in a wooden cart, on top of which the gun was placed.

IV. INITIAL OPERATIONAL PERFORMANCE

A. ELECTRICAL PERFORMANCE TESTS

The power supply was put through a series of test firings in an attempt to determine its inherent inductance, judge the performance of the TVS-40 switch, and assess the robustness of the design. Initial test firings were performed without the current transformer connected. A six inch square, twelve inch long, block of graphite, was used as a dummy load. The graphite block was sandwiched between two 1/4" plates of copper and had a measured resistance of 0.93 m ohms. The output cable of the power supply was passed through a ferrite toroid which had a three turn loop attached around it. The output of the toroid was connected to a Tektronix 602A Digitizing Signal Analyzer via a shielded coaxial cable with a 40 dB inline attenuator and recorded the temporal derivative of the current, $\frac{di}{dt}$, during the discharge.

The first series of firings were conducted with low voltages on the capacitor bank (2-3 kV) and served to check the electrical continuity of the system and the ability of the trigger circuit to successfully fire the TVS-40. The TVS-40 proved to be extremely reliable and operated well even when transferring pulses of less than a Coulomb. As the test firings approached capacitor voltages of 5 kV there was considerable flexing of the power supply cables and above 7 kV some of the cable terminations failed. The cables were reterminated with four mechanical connectors in series for each connection. The power supply was then tested up to a full 10 kV without any problems. The ferrite toroid used for recording the changes in current during the discharge was placed around the output cables of the power supply just downstream from the TVS-40 switch.

The traces shown in Figure 14, were obtained by discharging the power supply, with a capacitor bank charge of 5kV, through the dummy load. The first trace
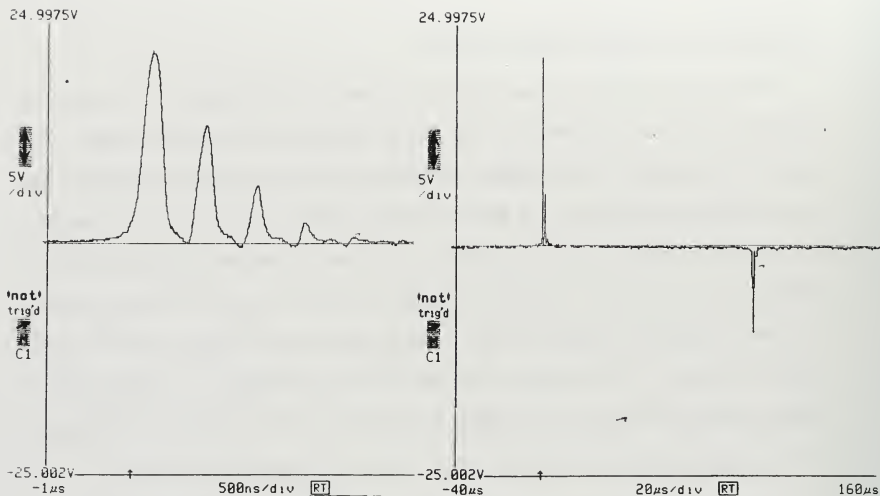
Figure 14. Power supply discharges at 5 kV capacitor voltage .

indicates a very rapid current rise time on the order of 2.5 µs. The compressed time scale of the second trace shows a current drop off over the same time scale as the rise and a total pulse duration of approximately 100 µs. The only known inductance of the power supply was the 40 nH of each of the capacitors. This was not near enough to account for the 200 µs ringing observed during the dummy load tests. This ringing period indicates that the total inductance of the power supply is 2.8 µH, the majority of which comes from the geometry of the connecting cables.

To further characterize the nature of the power supplies discharge, a voltage divider was installed across the vacuum switch and monitored during another series of dummy load firings. Of interest here, was the time required for the capacitors to drop

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from their charge voltage to zero. This voltage drop time would provide an empirical method of measuring the average current generated during the initial voltage drop. Figure 15 shows a trace of the capacitors voltage as the power supply was discharged from 5 kV into the dummy load.
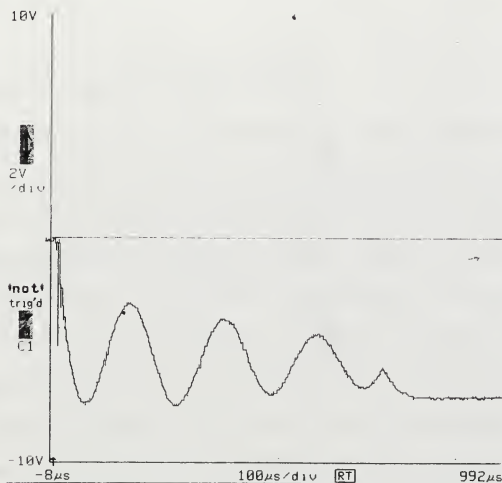

Figure 15. Switch voltage during a 5 kv discharge.

This trace confirms the 200 µs ring time observed during the previous tests and shows an initial voltage drop time on the order of 25-30 µs.

The power supply was next connected to the current transformer and the same dummy load was placed between the leads of its secondary. A similar series of graduated voltage firings was conducted up to a full 10 kV with no problems noted except for the generation of some rather large magnetic fields. For this set of tests,

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the first toroid was left in place and a second was placed around the output cable of the transformer's secondary. The traces shown in Figure 16 were again obtained from discharges conducted with a capacitor bank charge of 5 kV. The first is the output of the power supply and the second is the output of the current transformer.
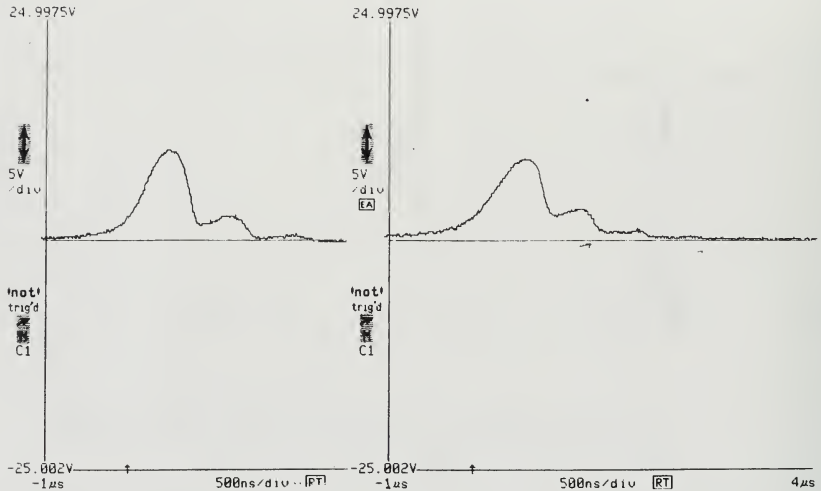

Figure 16. Power supply and transformer output at 5 kV.

The power supply's output shows a decrease in the rate of current rise as compared to that without the transformer in the circuit. This is probably due to the increase in the overall inductance of the circuit with the transformer installed. The calculated inductance of the transformer is 22.6 μH and is the dominant inductance of the circuit. The time period of the current pulse with the transformer in line was measured at 280 μ sec. From $\tau = 2\pi\sqrt{LC}$, the actual inductance for the circuit is 19.8

μH which is only 12% less than the calculated value. This series of tests, both with and without the current transformer in the circuit successfully demonstrated the robustness of the power supply and its components including the TVS-40. The only unexpected result was the apparent ringing of the capacitor bank through the TVS-40 switch. It is not clear if this is a failure of the TVS-40 to properly rectify the circuit or if the switch is being retriggered by oscillatory fields generated within other components of the power supply.

B. FIRING WITH CURRENT TRANSFORMER

The first ten test firings were conducted with disk shaped graphite projectiles at a capacitor bank charge of 5 kV (5 kJ). The magnetic field generated by the current transformer interfered with the chronograph which was being used to measure projectile velocities. Several different attempts to shield the device were unsuccessful and no reliable velocities were recorded. Additionally, each firing left a heavy residue of soot in the first few centimeters of the bore. This soot, which obscured the plexiglass windows used for the IR trigger had to be cleaned away between each shot.

The graphite projectiles had a close tolerance fit between the rails but had a loose fit vertically in the bore. It appeared that as the initial surge of current passed through the graphite, a plasma of ablated graphite would form and take over as the path for the current flow. At this point the low mass plasma cloud would be rapidly accelerated and "blow by" the projectile which would be left to coast down the bore from the force of its initial acceleration. This correlated with the visual observations of the firings which were characterized by a hypervelocity plasma jet exiting the bore followed by a low velocity (~100 m/s) projectile.

In an attempt to prevent the plasma blow by and to strengthen the rails the configuration of the gun was modified. A new, wider, pair of copper rails were fabricated which reduced the previously 3/4" wide rectangular bore to a 1/4" square bore. The channels in the phenolic blocks of the gun were deepened and the 1/16"

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phenolic bore sheets were replaced with 1/8" thick sheets of teflon. Finally, the IR sensor method of triggering the power supply was abandoned as the accumulated soot and damage to the plexiglass windows rendered them unserviceable. The new method of triggering the power supply was through an adjustable time delay which was set to initiate the current pulse 25 $m$secs after the compressed gas charge was applied to the breech.

The first projectiles/armatures fired with this new configuration were simply 1/4" square, 1/2" long pieces of graphite machined to a 0.003" fit in the bore. With the 100 psi compressed gas initiation and a 25 $m$sec delay, current flow initiated after approximately 2-3 inches of armature travel. Several shots were fired ranging from 5 kV to 7 kV of capacitor voltage. Unfortunately the velocities recorded by the chronograph were still erratic and indicated continued interference from the magnetic fields generated by the current transformer. The velocities appeared to be greatly improved over those from the previous gun configuration as the armatures were now penetrating several centimeters into a phone book which was being used as a backstop. However, the inability to accurately record projectile velocities led to the decision to disconnect the current transformer from the circuit.

C. FIRING WITHOUT CURRENT TRANSFORMER

With the Current transformer removed from the circuit, the power supply's cables were connected directly to the rails of the gun. The first shot was conducted at 5 kV charge with a graphite armature/projectile. The shot was very loud in comparison to those using the transformer. A velocity of 1200 m/s was recorded by the chronograph and the graphite embedded itself in the backstop. Upon examination of the gun, it was discovered that the rails had been bowed outward approximately 1/16" each in the area where current flow initiated. The rails were straightened, honed and reset in the gun, but this time shims were installed on the back side of the rails to prevent the possibility of further bending.

At this point, enough data had been gathered on the characteristics of the graphite armatures to indicate that they were not reducing the amount of erosion damage to the rails in comparison to aluminum as had been the case in the smaller, lower voltage gun. Several solid armatures were manufactured from both 6061 and 7075 aluminum alloys and fired from the gun at voltages from 5 kV to 10 kV. All of the armatures experienced severe erosion and on average lost approximately half of their mass during the shot. An assortment of the recovered armatures are shown in Figure 17, next to similar unfired armatures.
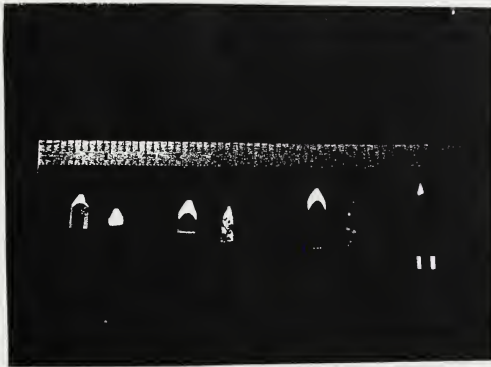
Figure 17. Fired and unfired aluminum armature pairs.

A typical 1 gram armature fired at a charge voltage of 10 kV achieved a velocity of 2,050 to 2,150 m/s and had a residual mass of approximately 0.60 grams. For these typical shots, the guns efficiency at converting the capacitor banks 20 kJ of stored energy into kinetic energy of the remaining armature mass was approximately 6.5%.

The significant reduction in the dimensions of the armatures made it apparent that these armatures were probably experiencing some degree of plasma blow-by towards the end of the current pulse. This lead to the manufacture of several projectiles which consisted of an aluminum armature attached to a block of nylon which contained a steel rod. As shown in Figure 18, the steel rod was 0.75" long, 0.18" in diameter and weighed 2 grams. The nylon sabot weighed 0.25 grams and served to electrically insulate the steel projectile and to prevent plasma blow-by of the aluminum armature. The armatures were made of 7075 aluminum and weighed 1 gram for a total projectile package weight of 3.25 grams.
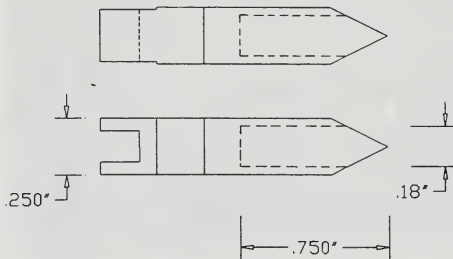
Figure 18. Two gram steel rod sub-projectile with nylon sabot and aluminum armature.

The first of these projectiles was fired at a power supply voltage of 12 kV. The steel rod passed cleanly through a 3" thick telephone book and was stopped by a steel plate backstop. The remaining 0.43 gram aluminum armature and several small

slivers of nylon were found lodged in the phone book. The measured velocity of the projectile was 1,973 m/s. For this firing, considering only the kinetic energy of the steel sub-projectile, the guns efficiency was 15%. The higher efficiency is attributed for the most part to the sabots ability to seal the bore and thereby contain the plasma generated by the solid armature as it transitioned. The firings were discontinued at this point due to the failure of the thyristor used to generate the pulses which triggered the TVS-40.

V. CONCLUSION

A One Meter Electromagnetic Railgun has been designed, constructed and successfully operated. Initial firings have accelerated a two gram sub-projectile to a muzzel velocity of nearly 2 kilometers per second with an overall efficiency of 15%. In the process, this work has demonstrated several important points. First, the understanding of the electromagnetic theory and the modeling of its behavior in these devices has reached a high level of maturity and should predict the behavior of a given design. The higher than expected velocities and efficiencies achieved with this gun are possibly due to the unanticipated ringing of the capacitor bank through the vacuum switch. This appears to have resulted in several large, short, current pulses which sequentially accelerated the projectile.

Secondly, the instrumentation of this type of device is critical, and as such needs to be an integral part of the design vice an after the fact add on. The present instrumentation of the test bed gun is inadequate to accurately and fully measure and record its electrical and mechanical characteristics. Unfortunately the cost of the instrumentation required may be far greater than that of the gun and power supply. This brings to light the last and perhaps most important point. Electromagnetic guns are inherently simple and inexpensive devices. Aside from the rather complex components presently required to trigger the large current discharges, the gun and power supply are just a basic, albeit large, LRC circuit. With further advances in high power SCR design and high density electrical energy storage devices, the complexity and cost of these guns should continue to decrease.

Areas of additional study with the one meter gun include the instrumentation of the gun to capture the actual current pulse generated by the power supply. With this ability, the nature of the discharge could be better characterized. This information could then be used to evaluate the affect of the current transformer on the circuit and its ability, if any, to improve the performance of the gun.

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